GEOMORPHOLOGY IN NEOTECTONIC INTERPRETATION

BY

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CONTENTS

INTRODUCTION

The surface of the earth is the most important natural structure known to man and it is essential to understand as much about it as possible. Internal and external forces control the shape and composition of the crust. Internal forces include tectonic movements and volcanism, while external forces include erosion and deposition. Tectonic geomorphology is the field of geology that deals with these forces. According to Wallace (1985), "Tectonic geomorphology is a rapidly evolving discipline that examines the interaction of vertical and horizontal earth deformation with erosional and depositional processes."

More advanced studies of the motions and rates of tectonic and geomorphic processes will lead to a better understanding of the crust. There are many new and existing techniques of study being used by geomorphologists in order to recreate Quaternary environments and in turn, determine the interaction of tectonics and erosional processes.

In this paper, I have researched the fundamentals of tectonics and their interpretation through goemorphic investigations. I have examined several processes that effect tectonics and the rates of these processes. I have also discussed changes in Quaternary climate and timescales used for dating geomorphic events.

OVERVIEW OF TECTONICS

When interpreting tectonics it is important to distinguish between tectostatic and tectodynamic structures. While both refer to tectonics, they have independent meanings. Tectostatics refers to the past static disposition which formed a present-day structure, while tectodynamics refers to the actual folding process. Confusion can result when superimposed tectonics are introduced. Superimposed tectonics are successive folding phases and each may have different orientation and extent. In other words, the tectostatic form of an area is changed by each tectodynamic event. In order to avoid confusion, when tectonics is mentioned in this paper, I will be refering to tectodynamic processes unless otherwise stated.

Geosynclines are structures in which most of the folding, faulting and earthquakes occur because they are unstable. Intense tectonic forces are found in geosynclines and these produce mountains and trenches with extreme gradients.

The orogenic phase of geosynclines produces the massive mountains though extreme uplift of the crust. Most of the time, compressional forces are responsible for the uplifted areas, such as with the collision of two plates, however, broad upwarping and tangential forces can also produce structures with great relief. When a section of crust is subjected to a broad upwarping, its upper surface is stretched to the point where it cracks. These cracks take the form of numerous parallel normal faults and, in the extreme case, produce a massive horst and graben landscape.

Decollement zones are formed when strata are stretched in a tangential direction, producing collapse structures. Decollements occur along more plastic horizons or along shear planes. Gravity can play a large part of the formation of decollements when large slices of strata slide past one another due to plastic flow or a zone of shear stress.

Thrust faults are another type of compression-induced structure, but produce low angle faults instead of the high angle normal and reverse faults. Thrust faults form when a bed or mass of beds becomes detached and is pushed well away from its original position. Klippen are erratics which are remnants of the overriding block.

All of the tectonic processes previously mentioned, produce structures which can be very difficult to interpret because of displacements, folding and discontinuities of strata. Erosion of a region with these structures makes interpretation that much more difficult.

Fault scarps can provide an excellent source of study for determining relative movements and rates of these tectonic processes. Before erosion, fault scarps indicate the amount and sense of movement of a fault. The surface of the scarp is the actual fault plane and the amount of slip can be determined by noting the displacement of beds. When slip is entirely vertical, a direct measurement of displacement can be made. Many times, fault slip is a combination of vertical and lateral displacements and more involved techniques must be used to determine net slip. The rates of fault movements, unless earthquake activated, are more difficult to determine because they occur at a very slow rate. Reconstructions of previous non-eroded scarps must be made in order to determine rates and can involve complicated studies.

INTERACTION OF TECTONICS AND EROSION

A variety of studies involving geomorpholgy, tectonism and pedogenics are needed to evaluate terrains, landforms and fluvial systems. As stated by Bull and Wallace (1985); "Applications use the shapes of hills, streams, fault scarps and marine terraces in order to better understand the locations, magnitudes and timing of late Quaternary uplift and/or horizontal displacement"(1985).

Recently, a widespread interest in time factors of geomorphic tectonics has helped to accelerate the application of studies in order to recreate the morphogenesis of the crust during the Quaternary. Along with the interest in time factors, are the recent advances in interpreting rates of horizontal and vertical displacements, erosion and deposition coupled with plate tectonics.

One of the most studied phenomena in tectonic geomorphology is mountain uplift and/or faulting and erosion. Mountain building normally produces massive structures and erosion can drastically increase the relief of the area or ultimately, reduce it to a peneplane. Folding, faulting and overthrusting can be induced by compressional forces in mountain belts and can drastically change the structure of them.

With the formation of these complicated structures, comes the likelihood of the formation of valleys which increase the rate of erosion when there is a significant gradient and non-resistant topography. Davis (1898) has shown that interpretation of mountain erosion can be more complicated than thought because mountain ranges are in cycles of erosion and uplift and the number of cycles completed may not be known.

Present-day mountains were formed and are forming through the interaction of tectonics and erosion. The sizes and shapes of these structures are dependent on the rates and types of tectonic activity and erosion.

STRUCTURES FORMED

Many features of mountains indicate the amount of erosion that has taken place since their primary uplift. These features include triangular facets, depth and maturity of valleys, sub-aerial deltas and sizes and shapes of eroded fault scarps.

Triangular facets are formed by valleys which have dissected the side of a mountain. Facets are actually segments of a fault scarp with their bases aligned parallel to the fault trace. When mountain valleys are well-formed or mature, very dominant triangular facets appear such as those of Maple Mountain, south of Provo, Utah (fig. 1).

The relative rate of formation of triangular facets can be estimated in several ways. The stratigraphy of the scarp is important for interpreting the rate of formation as a scarp with sedimentary or unconsolidated rocks will be cut

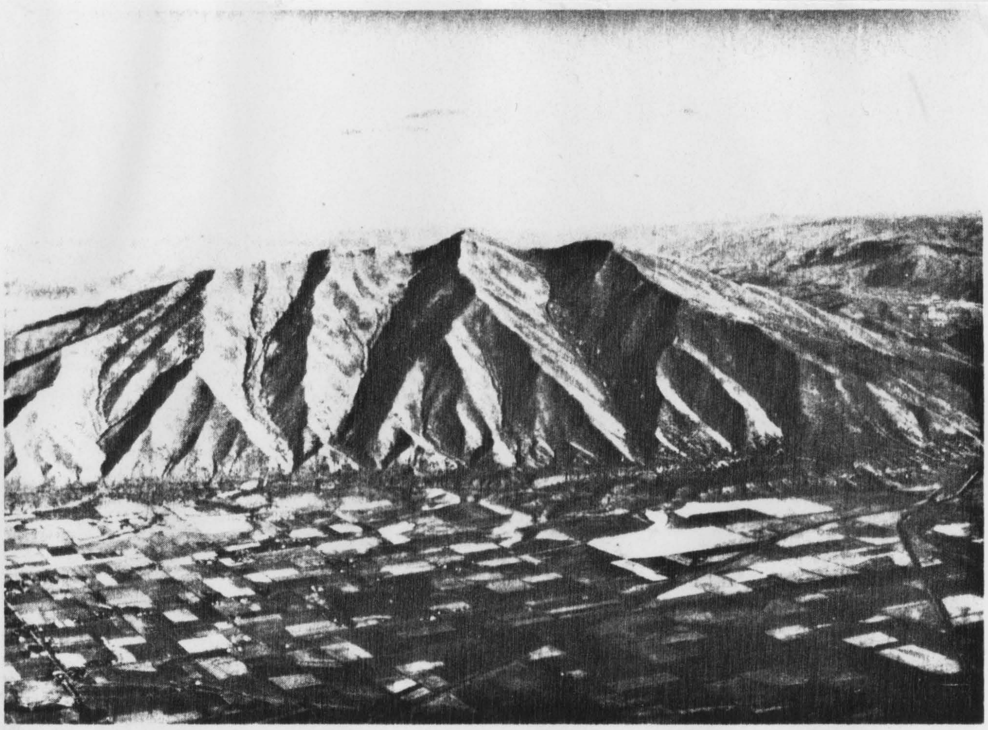


figure 1. Triangular facets aligned on the fault scarp of Maple Mountain, south of Provo, Utah. (From Bloom 1978).

much more rapidly than a scarp consisting of igneous or consolidated rocks. The slope of the scarp is directly related to the erosion rate because a steeper scarp will promote higher velocity runoff which gives the water higher erosion power. The rate of erosion of a scarp is also inversely proportional to the vegetation on it which tends to anchor the soil (Bloom 1978). Accurate determination of the rate of triangular facet formation involves careful determination of the previously listed factors and analysis of the climate of the area.

Erosion of a mountain occurs as soon as water is introduced to the system. A young mountain will have a relatively uniform surface and the adjacent valley will have little sediment in it and if the blocks remained rigid after faulting, an angular base (fig. 2). Erosion causes the surface of the mountain to become faceted and carved with stream valleys. The adjacent valley will slowly fill with sediment eroded from the mountain and it then becomes relatively flat or gently sloping (fig. 2). The figure shows the mountains before and after erosion and it is clearly evident that this mountain has achieved a relatively high degree of maturity. The Wasatch Mountains of Utah and the Basin and Range complex are this type of fault-block mountain.

Davis (1898) stated that there are three factors that must be considered when studying these types of ranges. First of all, a model of the mountains before erosion must

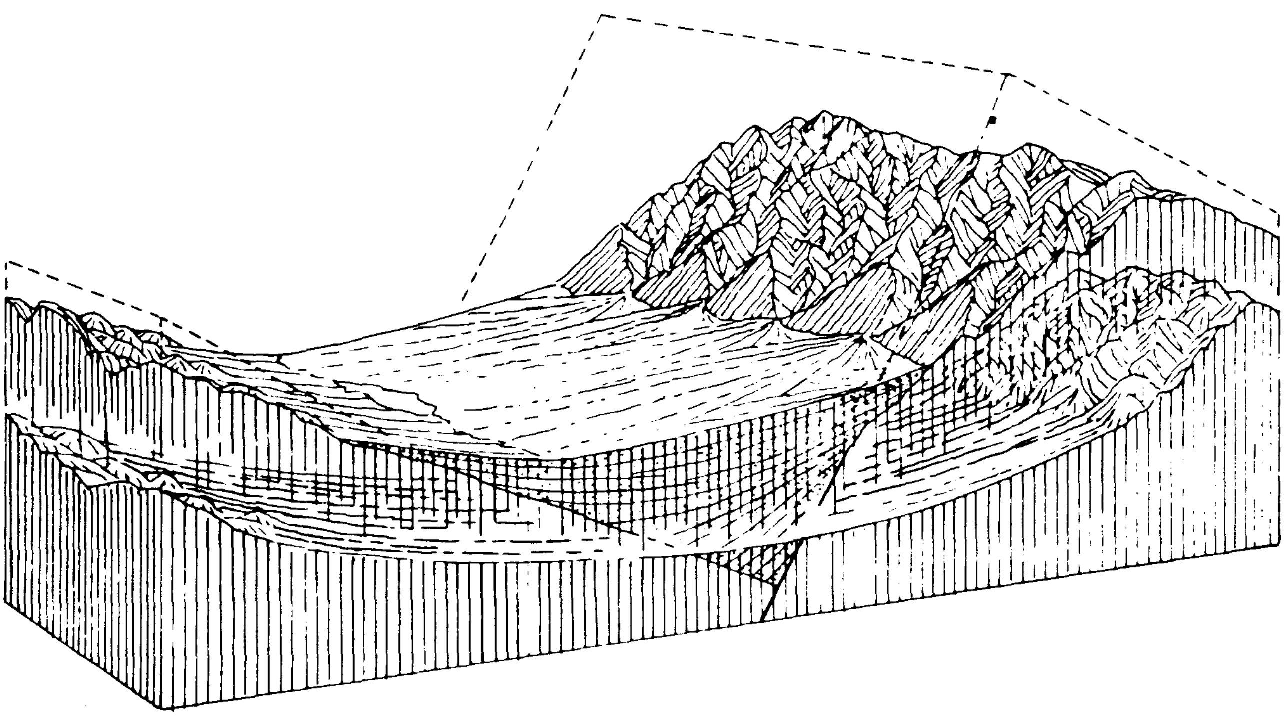


Figure 2.. Diagram of block mountains and intervening bolson in the Basin Ranges. Heavy dashed lines show the original form of the tilted blocks. Heavy lines show the region after vigorous dissection of the mountains and filling of the bolson, where a central playa receives interior drainage. Light lines show the region after more prolonged erosion; exterior drainage has been established, much of the bolson fill has been removed, and most of the lowland surface has become a rock floor, or pediment (from Davis 1898, fig 201).

be formed in order to interpret their metamorphism. Secondly, the structural changes of the mountain caused by tectonics must be investigated and finally, the erosional changes since the faulting must also be evaluated. Although these features are very important to the study of mountain belts, Davis does not state anything about the rates of formation or erosion which some geomorphologists criticize.

The rates of erosion of these structures is dependent on climate, including rainfall, temperature and altitude and the lithologies of the rocks present in the mountain.

The amount and rate of erosion in tectonic environments can be evaluated in a number of ways. Asymetric valleys indicate the relative resistivity of opposing bancks through differences in slope. When a stream cuts a mountain surface and forms a valley, the more resistant bank will have a steeper slope. The amount of erosion is noted by the amount of downcutting done by the stream.

Stream terraces and alluvial fans indicate changes in sediment load probably resulting from climatic fluctuations. Stream terraces above the present-day water level indicate past environments of low water velocity with high sediment load. Remnant stream sinuosity scars in terraces and in the presently-forming valley indicate lower water velocity at time of formation. Increased stream velocity due to increased precipitation or decreased sediment load, causes the stream to down-cut and straighten out because of increased power (Bloom 1978).

Dating past terraces can indicate the rate of erosion of the stream. The number of past terraces reveals the amount of time since the stream started to down-cut to the present level if all were formed in similar time periods. Determining the time interval for each terrace formation can be done using radiogenic or lichon dating and comparing successive terraces (Cullingford 1980).

Alluvial fans indicate past erosion rates in much the same as terraces in that aggradation occurs when sediment load is high and stream velocity is low. Correlation of alluvial fans and stream terraces has proven to be very helpful in recreating Quaternary environments.

By putting all of the information of tectonics and erosion together, geomorphologists are able to understand the forces that exist between the two.

FLUVIAL SYSTEMS AND DRAINAGE PATTERNS

When a block mountain, or a mountain created without compressional forces, is formed, it is shaped by the structures within it. After it is formed, erosional forces dominate the shape of the mountain. Various drainage patterns form on the mountain which are dependent on the surface configuration or structure. These patterns can be either consequent or subsequent (Bloom 1978).

Consequent drainage is controlled by surface configuration and can be of two types, definite or indefinite. Definite consequent streams flow along a fault trace, controlled by the fault scarp of one mountain and the backslope of the next (fig. 3). Indefinite consequent streams flow down the backslopes and the fault scarps (fig.3). These streams are called indefinite because they can flow anywhere on the slope surface and are not controlled to a path by structure.

Subsequent streams are controlled by the structure of the uppermost beds. These streams will flow in a particular pattern cutting beds which are most easily eroded.

If erosion permits, consequent and subsequent streams will develop valleys from which the amount and rate of erosion can be determined as previously mentioned.

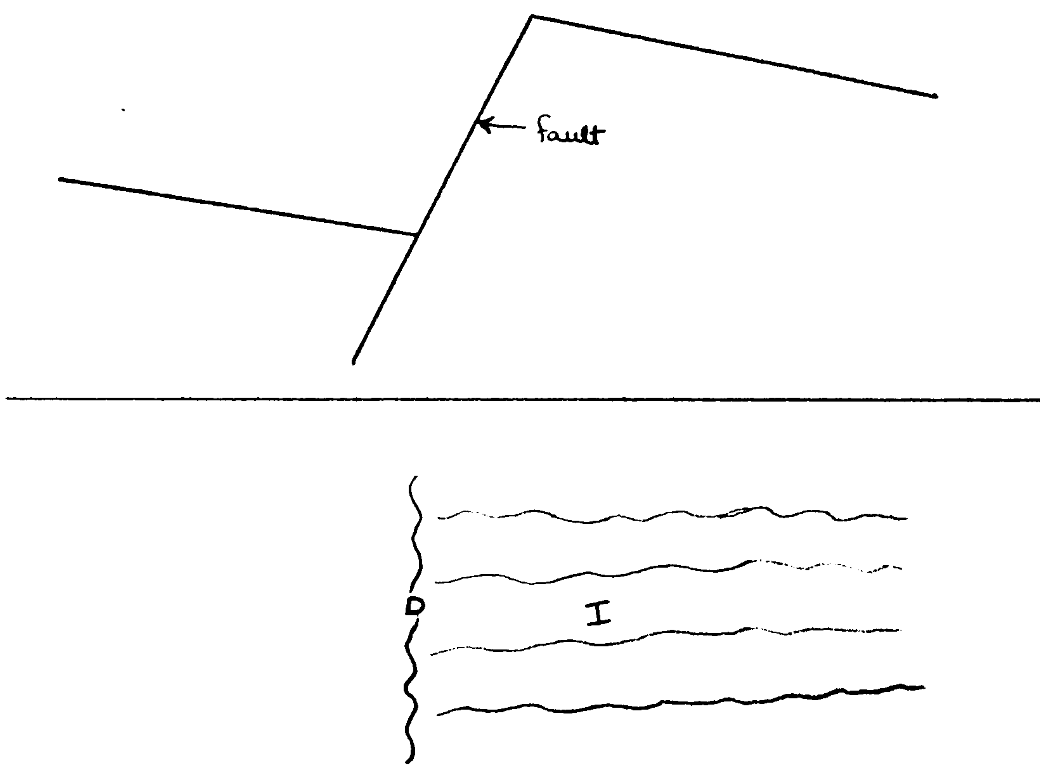


Figure 3. Definite (D) and indefinite (I)
consequent steams due to a fault.
(redrawn from Davis 1898).

THE MARINE CYCLE

Oceanic shorelines provide an excellent source of information regarding Quaternary climates and sea level fluctuations. Tectonically active coastlines are either submergent or emergent and through interaction with waves, form marine terraces.

TECTONICALLY PRODUCED TERRACES

Coastlines that are down-thrust by tectonics or covered by water due to increased sea level are called submergent. The headlands of these coasts are exposed to increased wave velocities and low-lying valleys are submerged. The headlands, in response to higher wave power, will be strongly eroded and will become rounded. These rounded headwalls will then be cut by the waves and cliffs will form. When the waves carry off the soil from the cliffs, it is deposited in deeper water, forming a terrace. An example of this type of shoreline is that of southeastern England (Davis 1898).

The inlets of a submergent coastline are subject to lower wave velocity because of the bending of the refracted wave fronts. Sediment will start to accumulate at the back of these inlets due to stream run-off slowing at the ocean, forming a delta. As more sediment accumulates, the delta will become sub-aerial and a bench will form. As deposition continues, beaches grow concavely towards the headlands. Expanding beaches cause erosion of the shoreline to decrease and finally end when all of the bays are filled and a smooth beach with inland cliffs remains. The progression of this type of shoreline is shown in figures 4 and 5.

A shoreline subjected to tectonic uplift is termed emergent and was previously the ocean-bottom. Wave action will carry small-grained particles out to deeper water and sediment at the breaking wave areas will be stirred up and carried out by currents and dropped, forming a sediment reef. The reef will continually grow upward and with the aid of storm surfs, it will rise above the water. This will then form a barrier behind which a quiet lagoon will form and eventually fill to form a tidal marsh. The fore-reef is then steepened due to cutting by tides. As shoreline maturity continues, the reef itself will be eroded leaving the tidal marsh which in turn, will be eroded. The mainland is then in contact with tides and is then under-cut, forming a bluff (fig. 6). Continued erosion of the mainland produces terraces that can be up to 100 feet high. Examples of these terraces can be seen along the California coast (fig. 7).

Some coastlines reveal numerous terraces, some higher than 100 feet which are assumed to have been formed by sea level fluctuations due to glaciation and tectonics in the Quaternary. Oceanic terraces are dated using radiogenic and paleontologic studies involving the organisms found on them. The rates of formation can then be determined by comparing terrace ages and past sea level fluctuations and valuable data regarding past oceanic activity can be deduced.

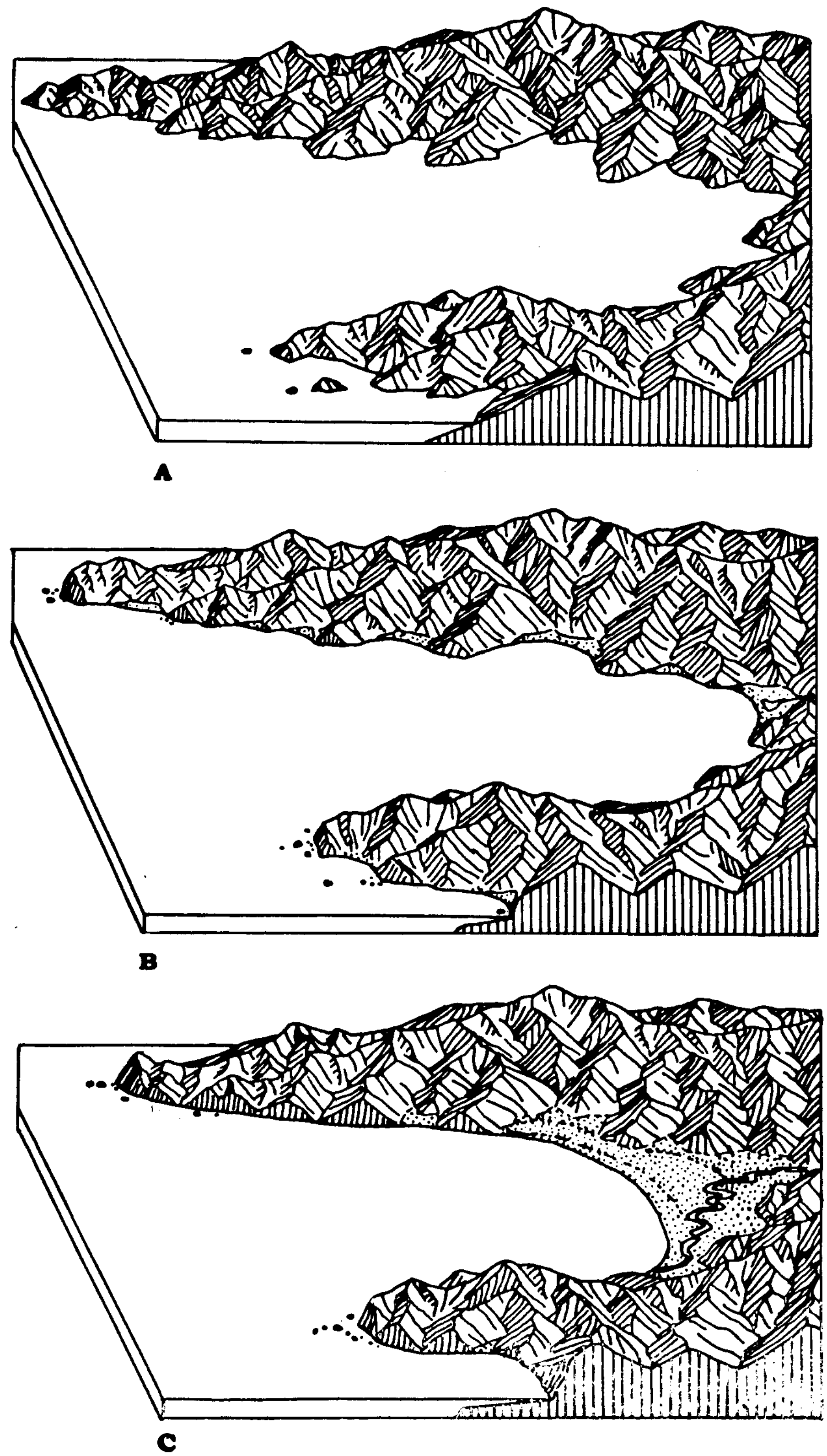


Figure 4. Figure shows the progression of a sub-mergent coastline from A (youngest) to C, showing the formation of a beach. (From Davis 1898).

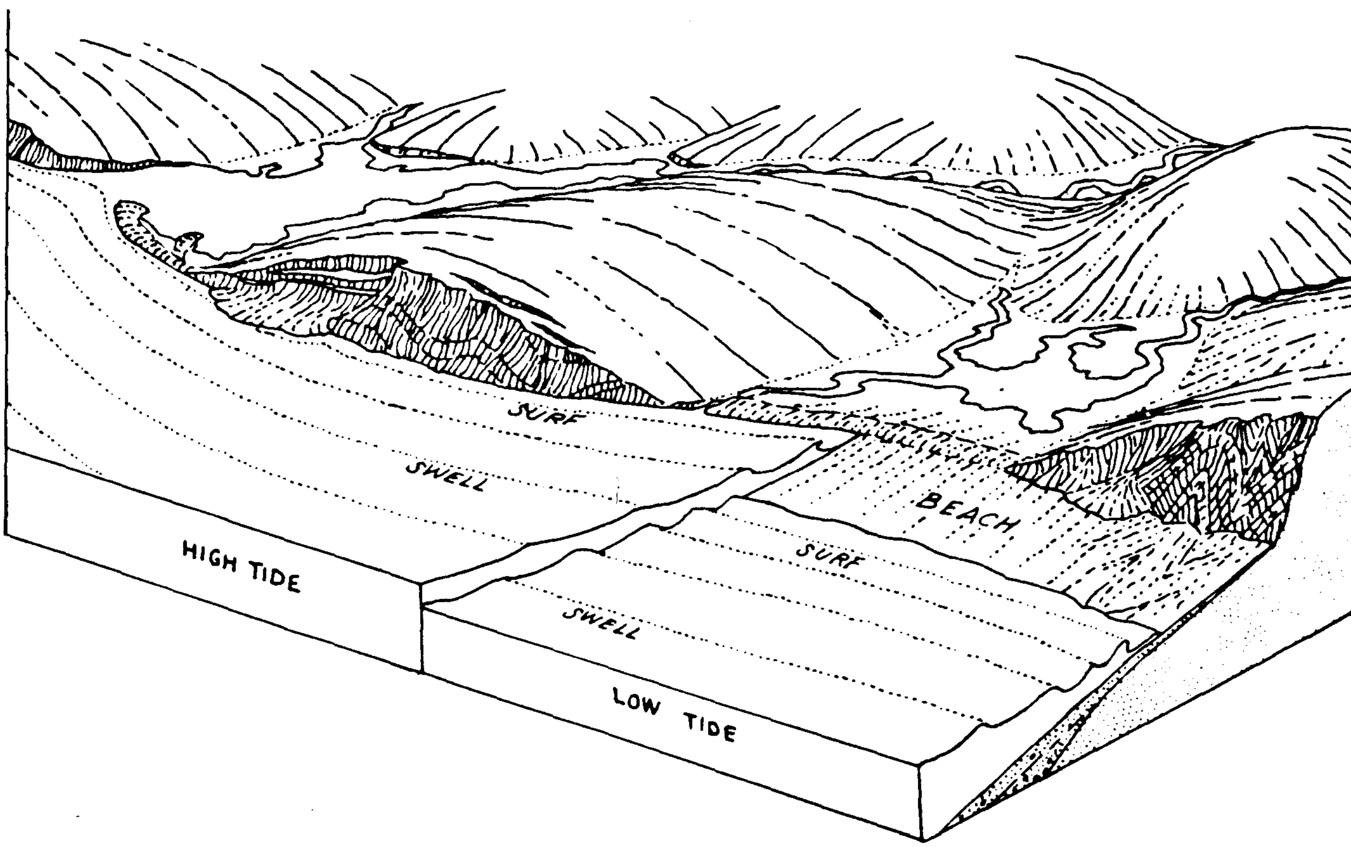


Figure 5. Diagram showing characteristic features of an embayed shoreline os submergence (From Davis 1898).

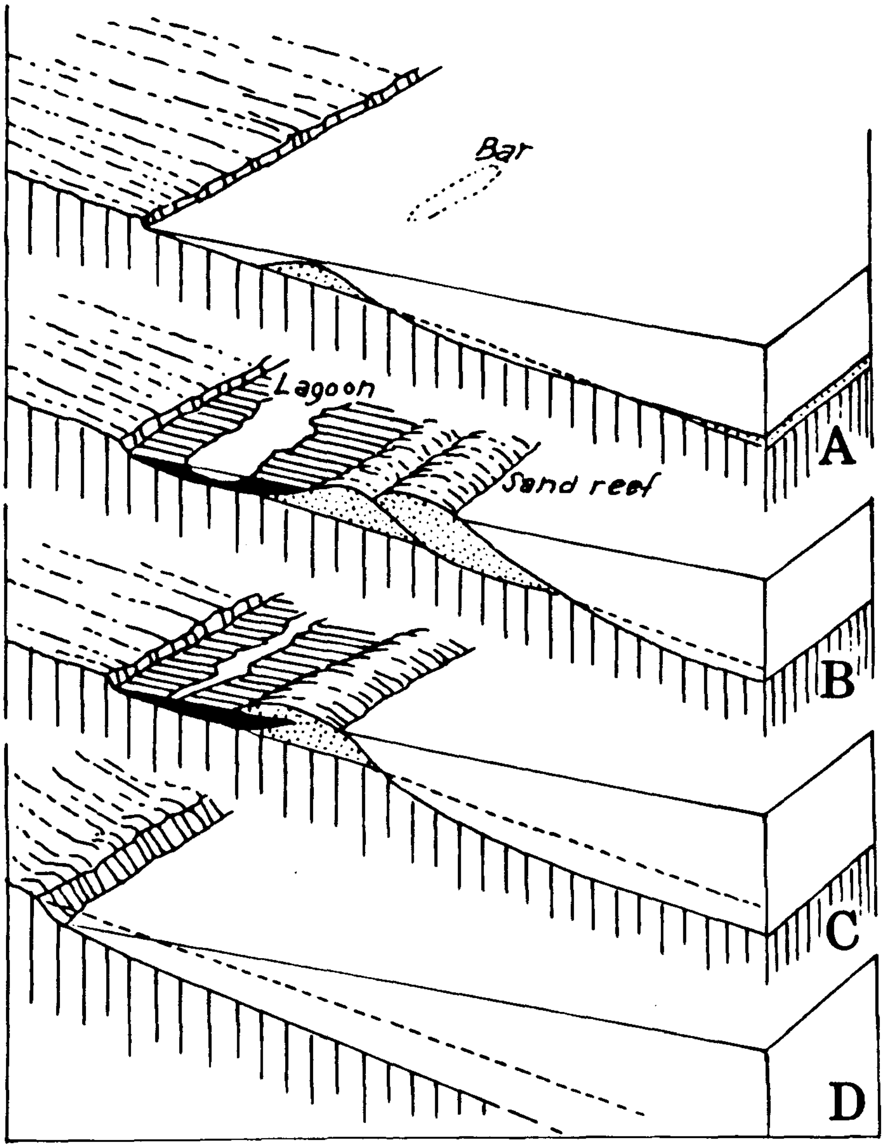
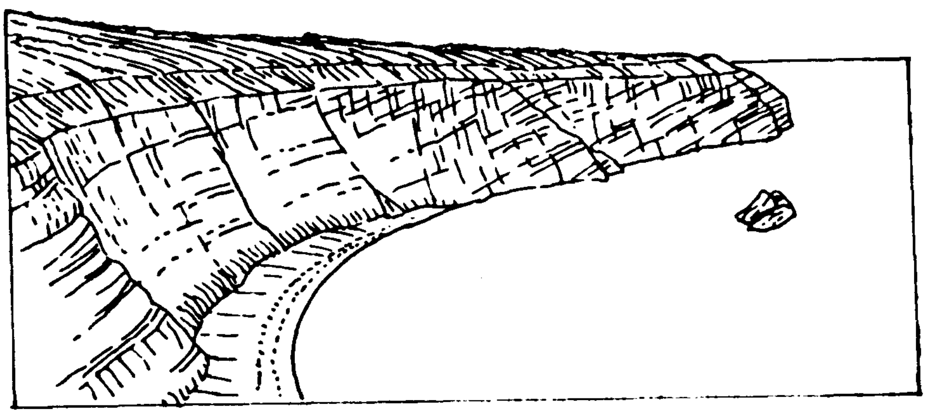
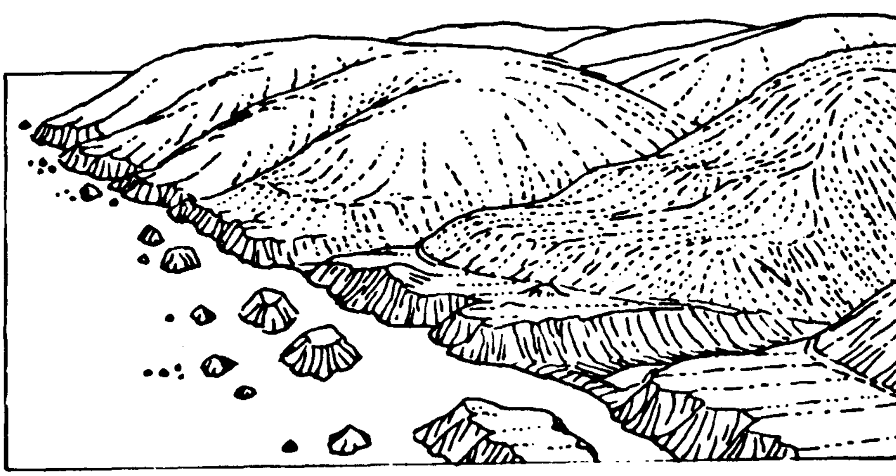


Figure 6. Stages in the development of a shoreline of emergence (From Davis 1898).



A



B

Figure 7. Uplifted marine terraces on the coast of California: A) A marine terrace 100 feet above sea level, truncating tilted Miocene strata; near Laguna south of Los Angeles. B) A strong lower marine terrace and two higher fainter terraces; on coast near Cape Vizcaino north of San Francisco (from Davis, 1933, figs 24, 26).

CORAL REEF TERRACES

Another type of marine terrace that can form is a coral reef. This type of terrace is built up from the skeletons of lime-secreting organisms in shallow, warm water. Most coral reefs form around oceanic islands where there is an abundance of calcium carbonate in the water. The three types of coral reefs forming today are fringing, barrier and atolls.

Darwin (1842) was the first to refer to these reefs as gradational because of their shapes. He studied Pacific island reefs during the voyage of the Beagle and proposed that fringing reefs were the youngest, followed by barrier reefs, with atolls being the the most mature. Darwin based his conclusions on the sizes of the reef-surrounded islands and the distance between these islands and the reefs that surround them. Figure 8 shows the morphogenesis of these reefs. Fringing reefs are very close to the island and through island subsidence and reef build-up, the reef-island distance became larger until there was little or no island in the center of the reef.

These features were later investigated by Davis (1898) on the Society Islands of the south-central Pacific. The chain of islands is about 200 miles long with the youngest islands at the southeastern end. Davis found reefless islands in the southeast progressing to fringing reef-surrounded islands to finally atoll reefs at the northwestern end, confirming Darwin's observations.

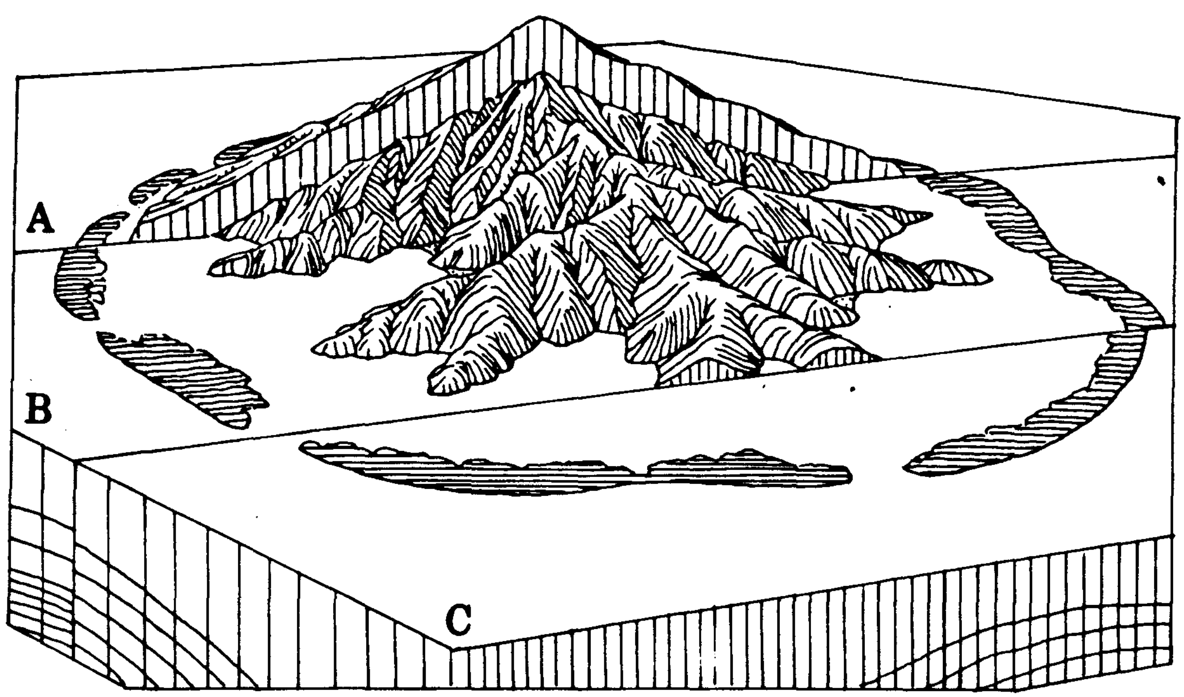


Figure 8. Three-stage diagram showing a subsiding island in a still-standing ocean. A fringing reef in the background block is converted into a barrier reef in the middle block, and into an atoll in the foreground block (from Davis, 1928, fig 20).

CORAL REEF AGE DETERMINATION

The amount of time needed to build the massive reefs in the Pacific was a topic of uncertainty at the turn of the century. R.A. Daly (1886) believed that the present-day reefs formed after the Pliestocene ice ages because he felt that the cooling of the water and sea level lowering would have been sufficient enough to destroy all existing reefs. Davis (1898) did not agree with Daly and postulated that the present-day reefs grew on pre-existing structures. This argu~~e~~ment has since been proven with paleontologic age determinations of species in the reefs (Cullingford-1980). Davis concluded that reefs formed around subsiding volcanic islands with the aid of sea level fluctuations.

Reef age determination has recently become an important factor in their study. Paleontologic age determination of corals and other reef-forming organisms was the most effective way of determining age in the past. Matching species ranges to the time of development of the reef is a good technique for long-lived reefs, but a better method has been developed for shorter time intervals. Radiogenic dating of corals leads to this more accurate age determination. This type of dating yields data from which the rates of development are still being studied and vary for different climates, so precise rates have not yet been published.

QUARTERNARY CLIMATE CHANGES

Climate plays a very important part in the amount and rate of erosion and recognizing past climate changes is vital to the understanding of an area.

Research was done on Greenland ice-cores with respect to changes in oxygen-18 content and results showed that major climatic changes have taken place in relatively short time periods (Dansgaard 1979). The observations revealed that the region changed from full glacial climate to inter-glacial in a few thousand years. One extreme cooling event, occurring 89,000 years ago, was discovered in the Greenland data. The data showed that the climate changed from warmer than today to ice age in about 100 years. These studies prove that temperature dictates climate and changes occurring rapidly must be noted for the correct interpretation of a past environment.

Values of oxygen-18 content in the ice-cores were determined for the last 800 years by Dansgaard (1979), and were compiled to show a temperature fluctuation curve (fig. 9). Dansgaard noticed that oxygen-18 fluctuations during the time interval between 1350 and 1500 resembles the present fluctuations and speculated that there will be a general warming trend toward the year 2000.

Wetherald and Manabe (1974) studied variations in solar insolation due to changes in solar luminosity and showed that there is a positive feedback between the greenhouse effect of

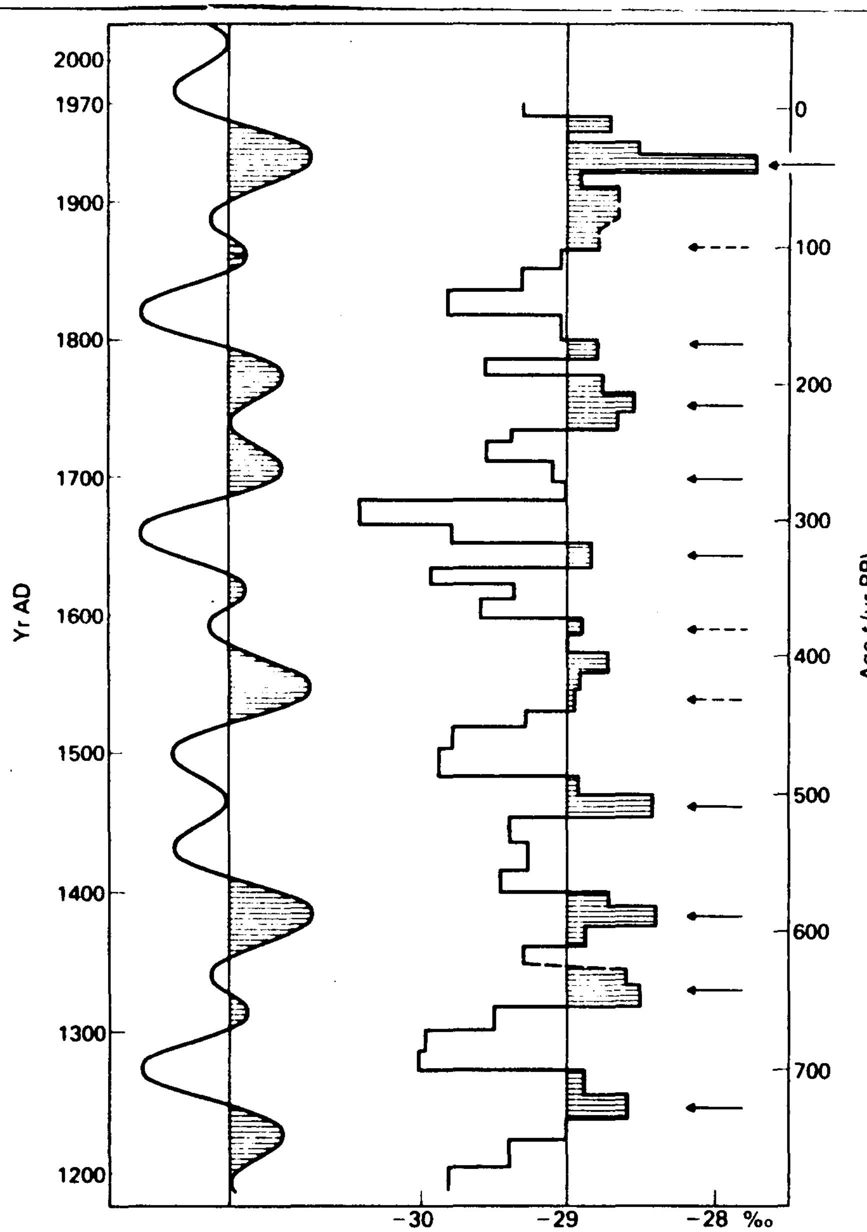


Figure 9. *Right:* oxygen-18 values of increments of an ice-core from north Greenland plotted against time *t* since the deposition of the ice. The hatched areas correspond to relatively warm periods.

Left: A synthesis of the two harmonics (78 and 181 years) that dominate the step curve. The curve from 1970 suggests the probable future climatic development (*after Dansgaard et al., 1971*).

water vapor and surface temperature. They used a mathematical model of the general atmospheric circulation and concluded that the feedback increases the sensitivity of surface temperature to changes in the solar constant by a factor of approximately two. Wetherald and Manabe also studied the hydrological cycle and found that a two percent increase in the solar constant caused up to a ten percent increase in the rate of precipitation. With their data, they plotted time versus the volume of ice sheets, mean surface temperature and changes in solar insolation and were able to correlate ice growth with solar insolation due to Quaternary orbital changes (fig. 10).

Past solar insolation and temperature fluctuations have helped geomorphologists to better understand past climates in order to explain Quaternary erosion.

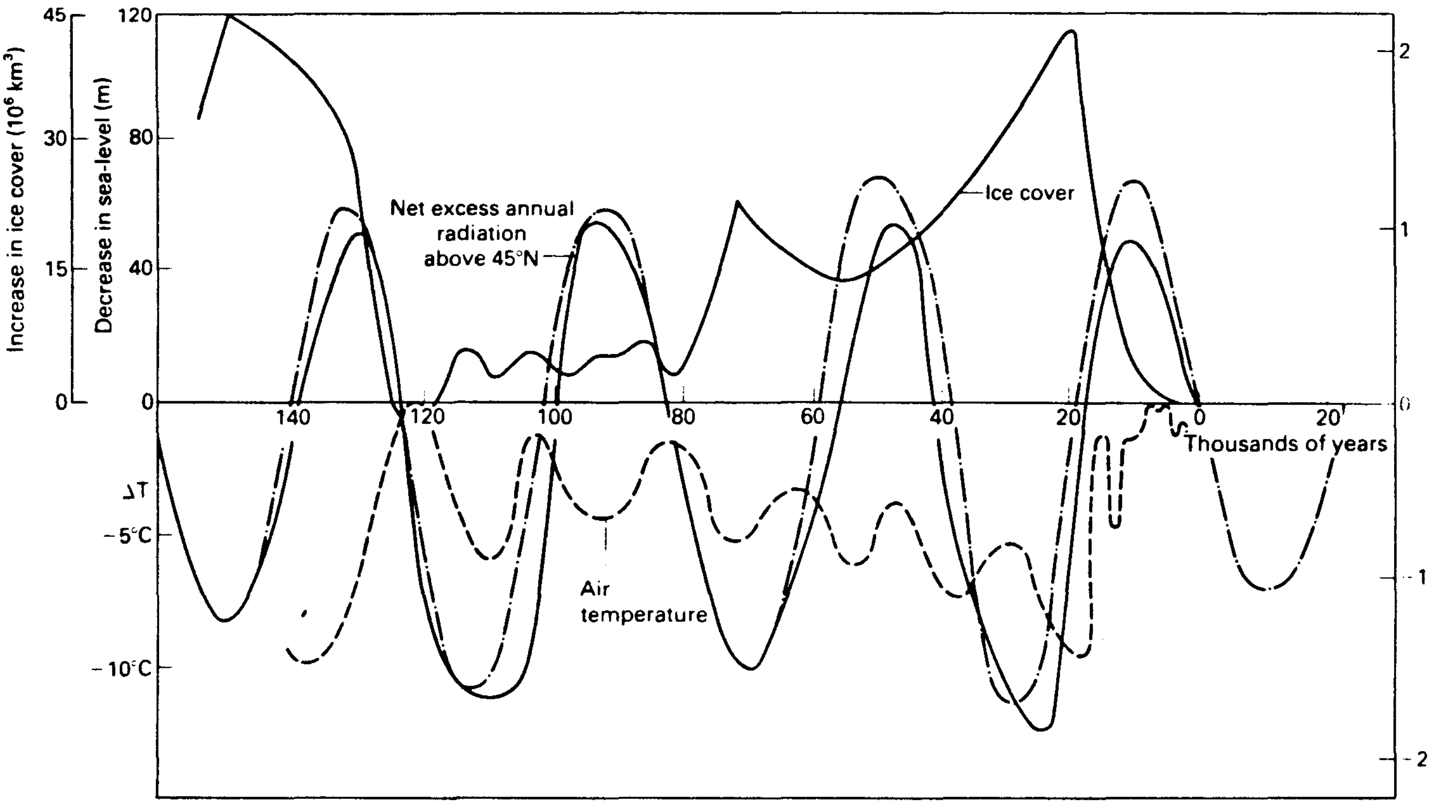


Figure 10. Changes in global ice cover, northern hemisphere air temperatures. and total insolation north of 45° N over the last 150,000 years. Total insolation plotted twice after Milankovitch and Vernekar (Lockwood 1979 after Mason, 1976).

TIMESCALES USED FOR DATING TECTONICS AND LANDFORMS

Dating geomorphic events and landforms is a young aspect of the science, having been expanded in the last twenty to thirty years. Prior to this time, geomorphologists studied morphogenesis of landforms without considering the rate or time involved with forming them. The incorporation of timescales into geomorphology has geatly helped in recreating geomorphic events and in doing so, geomorphologists are able to understand these events much better. John Lewin (1978) believes that the science of geomorphology lies somewhere between what is studied and sensory techniques, or dating and field work. The rates of geomorphic events are very slow compared to human events and this fact leads to the realization that geomorphologists need appropriate timescales for describing them.

In practice, four timescales are used by geomorphologists (Davidson 1980). The first is from field observations of processes and rates of change with experiments lasting up to ten years. Geomorphologists using this technique may encounter problems by only considering short-term data and not on past events which may be altering the system at the same time.

The second type of timescale examines historical data which may have a direct effect on past events which may be influencing the system. The historical data are compared with the field observations and a more complete model can be constructed. Historical data used include ground and air photography, maps, surveys, and remote sensing imagery.

The third timescale involves dating of exposed rocks and soils. Various techniques are used for dating, including dendrochronology, lichen dating and noting the relative weathering of rocks and soils.

The final timescale is based on stratigraphy which can yield relative and absolute age determination. Stratigraphic studies can include local and large-scale interpretations.

The best interpretation of an area is made by incorporating all four timescales into your work which eliminates the possibility of overlooking important features which could effect your results.

CONCLUSION

Tectonic geomorphology is a fairly young science which more and more scienists are turning to as a way of describing past, present and future tectonic and erosion amounts and rates. Understanding the relationship between these processes enables geomorphologists to interpret how erosion and tectonics effect each other. The determination of the rates of these processes is one of the newest interests in the science and will eventually lead to better reconstructions of Quaternary tectonic events and may also give insight to future processes.

The most important concepts that must be considered when studying geomorphic processes are structure,process and time (Bloom 1978). Structures and processes are the most understood by geomorphologists because they were thought to have been the most important factors for interpretation. In the past, time was studied relativistically and absolute of real age was not considered. New techniques of dating and interpreting rates of processes such as fault scarp erosion, marine terrace formation, and coral reef build-up have proven to be very important in understanding the morphogenesis of them.

Many new forms of research are being incorporated into the study of tectonics, including siesmology and magnetics which have only been around about fourty years, but have proven to be very complimentary to other studies. It is evident that there is much more to learn about tectonic geomorphology and with new advances in studies, it's only a matter of time that separates geomorphologists and its understanding.

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